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The Wind that Shakes the Barley: the role of East Asian cuisines on barley grain size

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Abstract

This paper investigates the eastern movements of barley grains and their morphological variations in prehistory. By combining previously published and newly collected archaeobotanical grain measurements (*n*=2,176), we explore the roles of culinary traditions underling the morphological traits observed. We find barley diminished in size as it moved from its origin in southwestern Asia to Central and East Asia between the 3rd millennium BC and 1st millennium BC. In particular, the grains in Monsoonal China became greatly reduced in comparison to other regions as the crop was incorporated into eastern small grain cuisines. The reverse pattern is observed in the high-altitude Tibetan environment, which is attributed to practicalities of cooking under low vapor pressure conditions. These results, demonstrating that barley moved eastward but western grinding and baking traditions did not, reveal the complexity of the eastern culinary system and raise awareness of decoupling of grains and their associated cuisines.

Keywords: barley, food globalization, ancient culinary practices, grain size, prehistory

Introduction

Increase in grain (caryopsis) size is often featured as a key measure of plants' 'domestication syndrome' (Zohary and Hopf 2000; Fuller et al. 2014, 2017). Larger grain size in the context of early cultivation is considered to reflect the productive benefits of the cultivated field compared to the wild habitat (Harlan et al. 1973; Allaby et al. 2021) . Between approximately the fifth and second millennia BC, however, the grain size of one of the world's most important crops, wheat, underwent a substantial reduction (Fuller et al. 2014; Liu et al. 2016). This pattern is likely the result of regional variation in eastern and western Eurasia as crops dispersed beyond their native ecological limits (Fuller et al. 2017). It is unclear, however, whether these variations reflect phenotypic plasticity or underlining genetic adaptation for compactness of the grain shape and spike (MacKey 1966; Mori et al. 2013). Scholars have hypothesized environmental adaptation could account for the observed trends (e.g. Spengler 2015; Fuller et al. 2017; Motuzaite-Matuzeviciute et al. 2018). In this paper, we shift the focus

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from the environments to cuisines, and consider the role of eastern food preparation practices in grain size variation of another Fertile Crescent originated cereal: barley. The aim is to assess whether morphotypes of eastward spreading barley were directly influenced by eastern culinary practices.

Between approximately 5000 and 1500 cal. BC, movements of several cereal crops from distinct domestication centers linked distant communities into a web of connections that spanned the entire Eurasian landmass (e.g.Jones et al. 2011, 2016; Liu et al. 2019). As part of this prehistoric 'food globalization', free-threshing wheat (*Triticum* cf. *aestivum*) and naked and hulled barley (*Hordeum vulgare)* spread from origins in southwestern Asia, through Central Asia into East Asia (e.g. Frachetti et al. 2010; Liu et al. 2017). Much has been discussed regarding the routes and chronologies of wheat and barley dispersals (e.g. Flad et al. 2010; Frachetti 2012; Barton and An 2014; Betts et al. 2014; Spengler, Frachetti, Doumani, et al. 2014; Liu et al. 2016; Zhao 2018; Motuzaite-Matuzeviciute et al. 2018, 2020; Zhou et al. 2020; Deng et al. 2020; Motuzaite Matuzeviciute et al. 2020; Tan et al. 2021; Tang et al. 2021), including the possibility of a very old maritime connection in the third millennium BC (Zhao 2009). During the second millennium BC, however, more substantial movements took place across the continent. A now well-documented trajectory is along the so-called "Inner Asian Mountain Corridor", a piedmont zone spanning from Southwest Asia through the Pamir, Tianshan, Dzhungar and Altai Mountains, and subsequently connecting to the Hexi Corridor (Frachetti 2012; Spengler 2015; Liu et al. 2016; Stevens et al. 2016; Motuzaite Matuzeviciute et al. 2020ab; Zhou et al. 2020). Further, the initial expansion of wheat and barley cultivation into ancient China might not have occurred simultaneously, but through distinct processes that likely took place over millennia via several pathways, including one over the southern Tibetan Plateau (Liu et al. 2017; Lister et al. 2018).

In addition to the ongoing research on routes and chronologies, scholarly attention has focused on understanding drivers underlining the 'Food Globalization' process. Among them, the social and culinary drivers and the context in which dietary innovation could occur have been debated (Jones et al. 2011; Boivin et al. 2012; Liu and Jones 2014). Central to our investigation are the differences in culinary traditions of early communities in East and West Asia: food processing techniques based on boiling and steaming of grain in the East, grinding grain and

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baking the resulting flour in the West (Sakamoto 1996; Fuller and Rowlands 2009). These deep-seated culinary differences, to some extent, explain the material distinction that has long been observed archaeologically between East and West Asia. While the Pre-Pottery Neolithic cultures of southwest Asia made extensive use of querns for flour production and constructed clay ovens for baking bread and roasting foods, communities in Neolithic (and Paleolithic) China utilized elaborate pottery vessels for 'wet-cuisine' based on boiling and steaming. Fuller and Rowlands (2011) suggest these East-and-West culinary differences are deeply embedded, associated with Pleistocene hunter-and-gatherer's food traditions, and are thus intertwined with the later domestication process and transition to agriculture.

Questions remain as to what happened when grains like wheat and barley, which originated in southwest Asia amidst longstanding baking and breadmaking traditions, were introduced into a different culinary arena, one that favored boiling and steaming whole grains. For wheat, archaeobotanical evidence shows that introduction of this grain into China may have involved selection for reduced grain size adapted to the eastern boiling-and-steaming tradition (Liu et al. 2016). Similarly, in southeast Asia, the preference for the cultivation of cereals that show within-species variation for stickiness of the cooked grains are typified by the eastern boiling-and-steaming cultures (Fuller and Castillo 2016).

Grain size is routinely recorded by archaeobotanists during analysis. It is thus well suited for macro-scale analyses across multiple sites and regions. It should be noted, it is a quantitative trait (rather than a qualitative one such as the presence of tough rachis) that can only be measured on the level of population/assemblage. Grain size analysis needs to take into consideration the effect of charring, which can lead to caryopsis distortion. Various experimental heating studies demonstrate that grain morphology is sensitive to charring conditions, especially temperature, which often leads to increase in breadth and decrease in length (e.g. Stewart and Robertson III 1971; Ferrio et al. 2004; Braadbaart 2008; Charles et al. 2015). Charring conditions can be verified using a combination of grains' internal and external features. Given the geographical scope, such large-scale assessment is currently incomplete. However, the distorted grain type is infrequently the main grain state at well-preserved archaeological sites (Styring et al. 2013), which is the primary context under consideration in this study. Physiological differences also exist between major varieties and subspecies, including hull-less

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grains and multiple rows of fertile florets (Fuller and Weisskopf 2014). These aspects are considered in detail below.

We use grain measurements to track changes in barley grain size across Asia, and hence to evaluate the role of regional cooking variations in morphotype differences. We find, similar to free-threshing wheat, barley grain size was diminished as it moved from its origin in southwestern Asia eastward to East Asia.

Materials and Methods

Materials

We assembled 2,176 carbonized barley grain measurements from published reports and previously unpublished data from South Asia (n=277, 13 sites), Inner Asian Mountain Corridor (IAMC) (n=965, 11 sites), Monsoonal China (n=377, 34 sites) and Northeast Asia (n=557, 72 sites), totaling 130 sites. Compiled samples range from the 3rd millennium BC to the early 1st millennium AD. We collected measurements for length, breadth, and height of the barley grains. The majority of the data report individual grain measurements (site n = 83). However, some source studies (site n = 47) did not report individual measurements, only site means, which we also included in this study in order to incorporate as much data as possible. The vast majority of these averaged samples come from Northeast Asia (n = 34) and are not a major focus of this study. We note this could bias against sites with mean values only and acknowledge the limitation of the data. However, when the analysis is carried out using single grain measurements only, the pattern persists (Supplementary Figure 4).

Length and breadth measurements were chosen as the focus of this study as all collected data included both of these measurements. It is documented that height (thickness) and breadth ratio could be linked to the domestication process (Fuller et al. 2017). Unfortunately, height measurements were not reported consistently in the compiled studies and would thus preclude a complete analysis. Husk types such as 'hulled' or 'naked' were collected when reported, along with associated elevation and location information. Six- and two-row barleys were not separated due to morphological overlap between the two forms and a lack of rachis evidence in many assemblages. The original archaeobotanical analysis and measurements of grains were performed at respective laboratories and final meta-data analyses compiled and analyzed at Washington

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University in St. Louis, Laboratory for the Analysis of Early Food-Webs. Figure 1 presents collected data and grain type by region, while Supplementary Figure 1 and 2 present data by time period. **Error! Reference source not found.** provides a summary of all data, with means and standard deviations given for sites where individual grains were originally reported. In the subsequent analyses, individual datapoints rather than summary statistics are used.

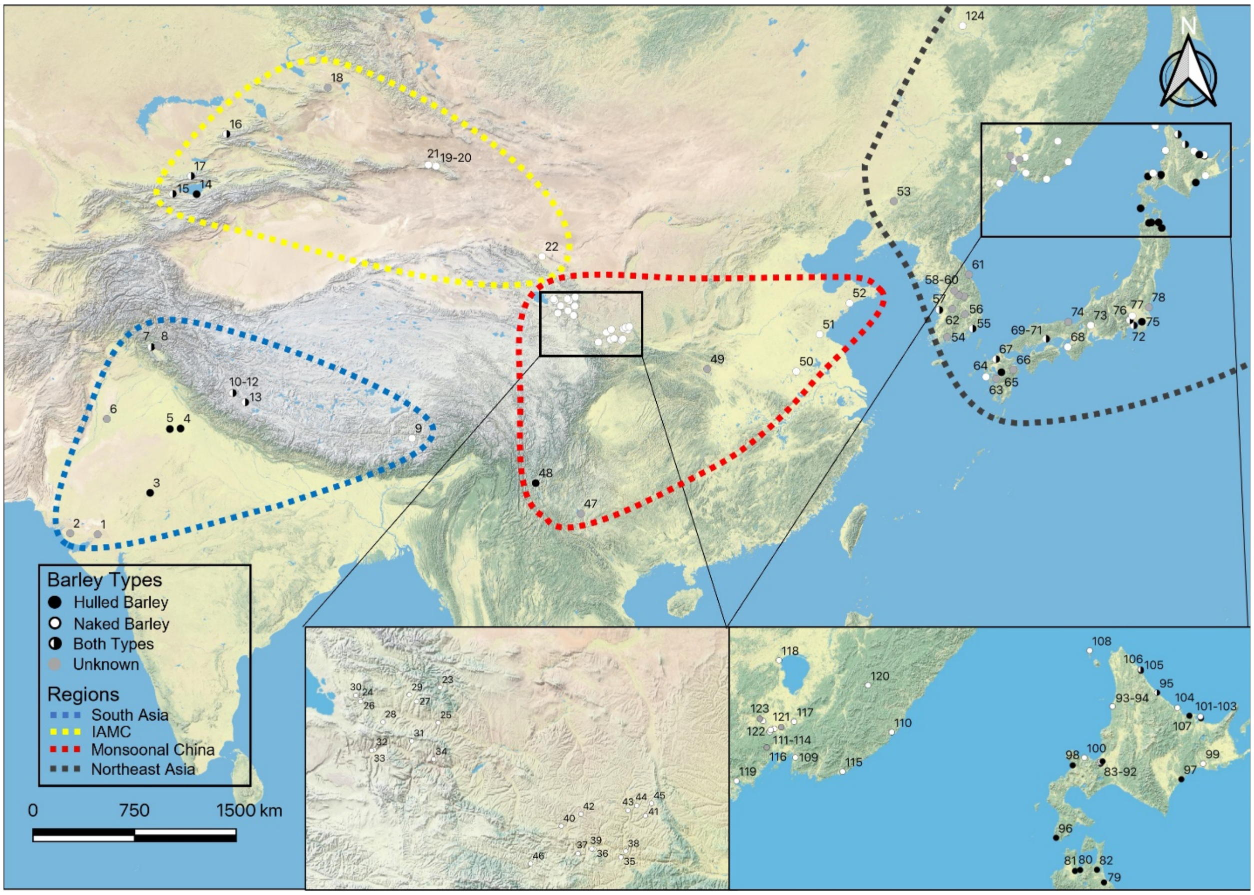

Figure 1. Map of sites analyzed. Regional boundaries are superimposed, and grain hull-type symbolized by point color. Site numbers are detailed in **Error! Reference source not found.**.

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Methods

Data visualization and statistical analyses on assembled data were performed in R, version 3.6.1. A normal distribution test (Shapiro-Wilk) found the dataset to not be normally distributed. Therefore, Kruskal-Wallis test (for non-normal analysis of variance) was conducted. Multiple comparison post-hoc test tested the significance of variances. Welch Two Sample t-test was conducted to examine variance between regions through time. Full results can be found in Supplementary Tables 2 and 3.

We categorized the data points based on their site origin and reported radiocarbon or typochronological date range. According to archaeological, geographical and cultural similarities, sites were grouped into the broader regions of South Asia (broader Indus, northwest India, western and southern Tibet), an extended Inner Asian Mountain Corridor (the piedmont zones spanning through Pamir, Tianshan, Dzhungar and Altai Mountains and western Hexi corridor), Monsoonal China (eastern China under the influence of summer monsoons including the Loess Plateau, Yellow River and Yun-Gui Plateau) and Northeast Asia (South Korea, Japan, and the far East region of Russia) (Figure 1).

Broad geographical trends were assessed with all data regardless of time period. Further, we analyzed a subset of the data whose chronology dated to after 1000 BC, when barley became widespread in eastern Asia (Liu et al. 2017). Our statistical analysis of these datasets indicates an even more pronounce trend in measurement differences between regional contexts in the post 1000 BC dataset (Supplementary Table 2).

Results

Regional barley measurements

The smallest mean grains (by length) appear in Monsoonal China (length: 4.27 mm, breadth 2.72, height: 2.07) and the largest in South Asia (length: 5.02 mm, breadth: 3.09, height: 2.06). Monsoonal China has the most compact barley with a length/breadth ratio of 1.59 mm and Northeast Asia has the most elliptical with length/breadth ratio of 1.70 mm. Visual representation of regional grain measurements show a reduction in grain length from South Asia to Monsoonal China (roughly west to east) (Figure 2; Table 1). Northeast Asian grains are much larger than Monsoonal China, but similar to both South Asia and IAMC.

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Table 1 Summary of grain measurements from South Asia, IAMC, Monsoonal China, and Monsoonal Asia. Mean length, breadth, height and length/breadth ratio and total counts are reported, including how many are calculated mean measurements and how many are single grain measurements. Measurements are in mm.

Region	Length $\bar{x}$	Breadth $\bar{x}$	L/B $\bar{x}$	N	N Sites	N mean measurements	N single grain measurements
South Asia	5.02	3.09	1.65	277	13	0	277
IAMC	4.68	2.9	1.63	965	11	2	963
Monsoonal China	4.27	2.72	1.59	377	34	4	373
Northeast Asia	4.95	2.91	1.7	557	72	58	499
Total	4.72	2.9	1.64	2,176	130	64	2,112

To clarify these trends in grain size between regions, statistical analyses were used to assess differences in mean length and breadth measurements between regions. These and all following statistical results are available in Supplementary Tables 2 and 3. There is a statistically significant difference in mean grain size between regions for both length, H(171.89) =3, p = 2.20E-16, and breadth, H(55.586) =3, p = 5.15E-12. Post-hoc multiple comparison tests specified that all length measurement relationships are significantly different except between South Asia and Northeast Asia, ($p< 0.05$). For breadth, all measurement relationships are significantly different except between the IAMC and Northeast Asia, ($p< 0.05$).

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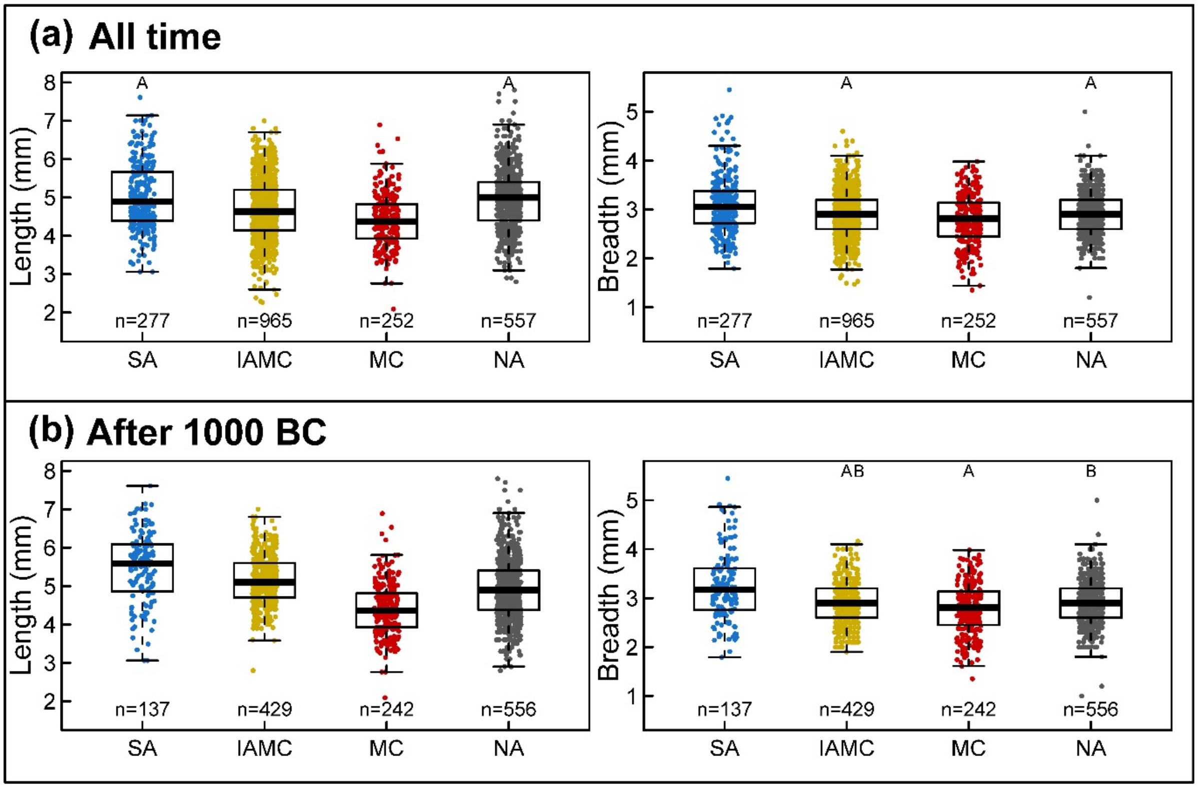

Figure 2 Boxplots of regional barley measurements: (a) from all times periods, (b) from after 1000 BC. Length measurements are in the left panel and breadth measurements are in the right panel. Nonsignificant relationships share letters, all other relationships are significant, $p<0.05$.

Elevation

We use a scatterplot to visualize the grain measurements in relationship to site elevation (Figure 3, for breadth see Supplementary Figure 3). Data points represent the calculated mean grain measurement for each site, which are color-coded based on region. Northeast Asian grains were excluded from these analyses as the data are substantially later in time (most after 1000 AD) and few sites had reported elevational data available. While no clear relationship is seen between altitude and grain length in any of the regions, the grains originating at the highest altitude (Tibet, blue triangles) constitute some of the longest grains in the entire assemblage, particularly those from the sites of Dingdong, Bangga and Kaerdong.

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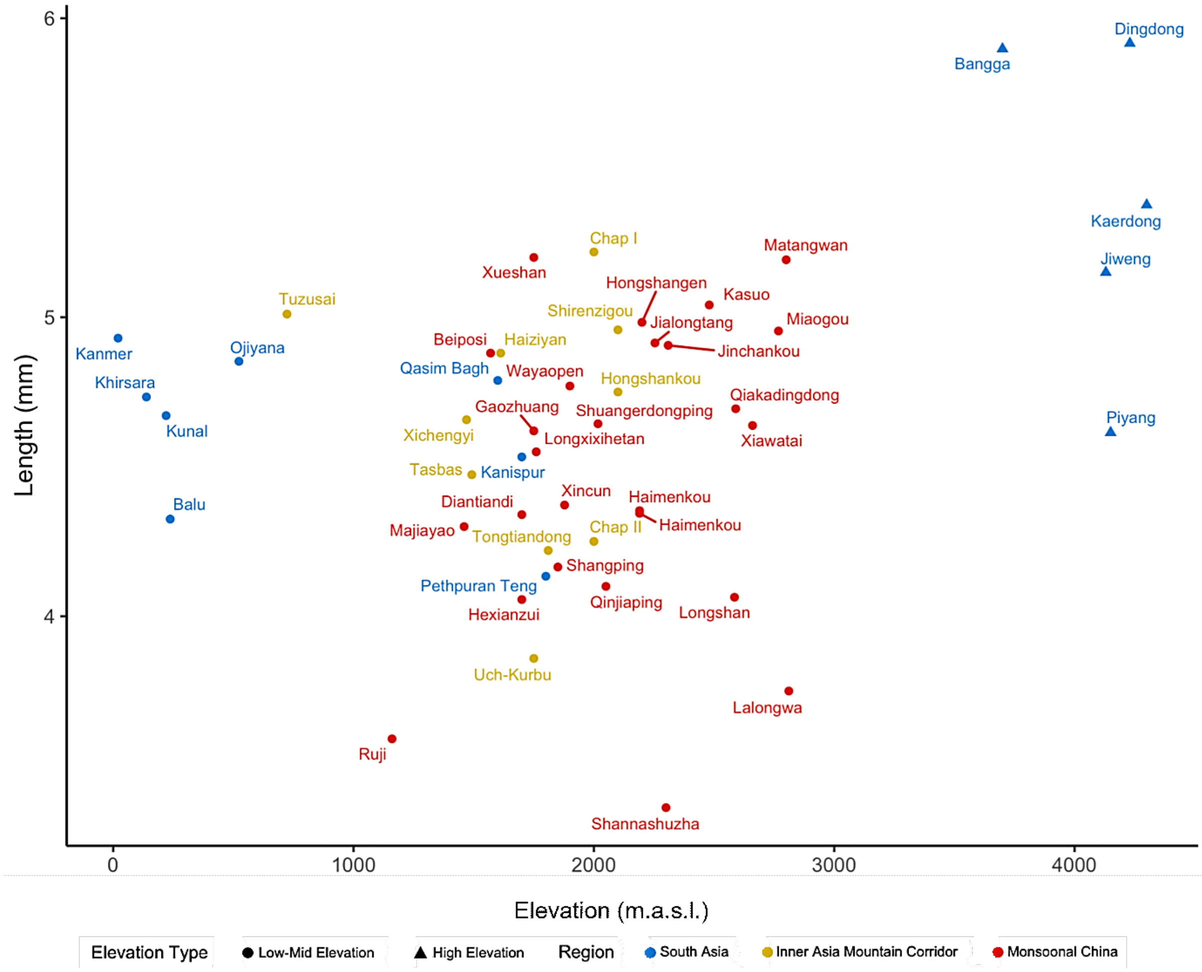

Figure 3. Scatterplot of relationship of mean grain length from all sites (excluding Northeast Asia), y-axis, and elevation of sites, x-axis. Sites are colored representing region, and points represent low-mid elevation and high elevation.

Hulled and Naked Barley

The data show clear regional differences in husk types. In South Asia, IAMC, and Northeast Asia, both hulled and naked morphotypes were widespread whereas in Monsoonal China, only naked grains were predominant (with the exception of sites in the Yun Plateau) (Figure 1). When we compare grain metrics across the regions, similar trends are present in both hulled and naked morphotypes (Figure 4, Supplementary Table 4). Both morphotypes reduce in length in the IAMC and Monsoonal China regions. These trends are present when all time periods are analyzed, Figure 4 (a) and (c), and for after 1000 BC Figure 4 (b) and (d).

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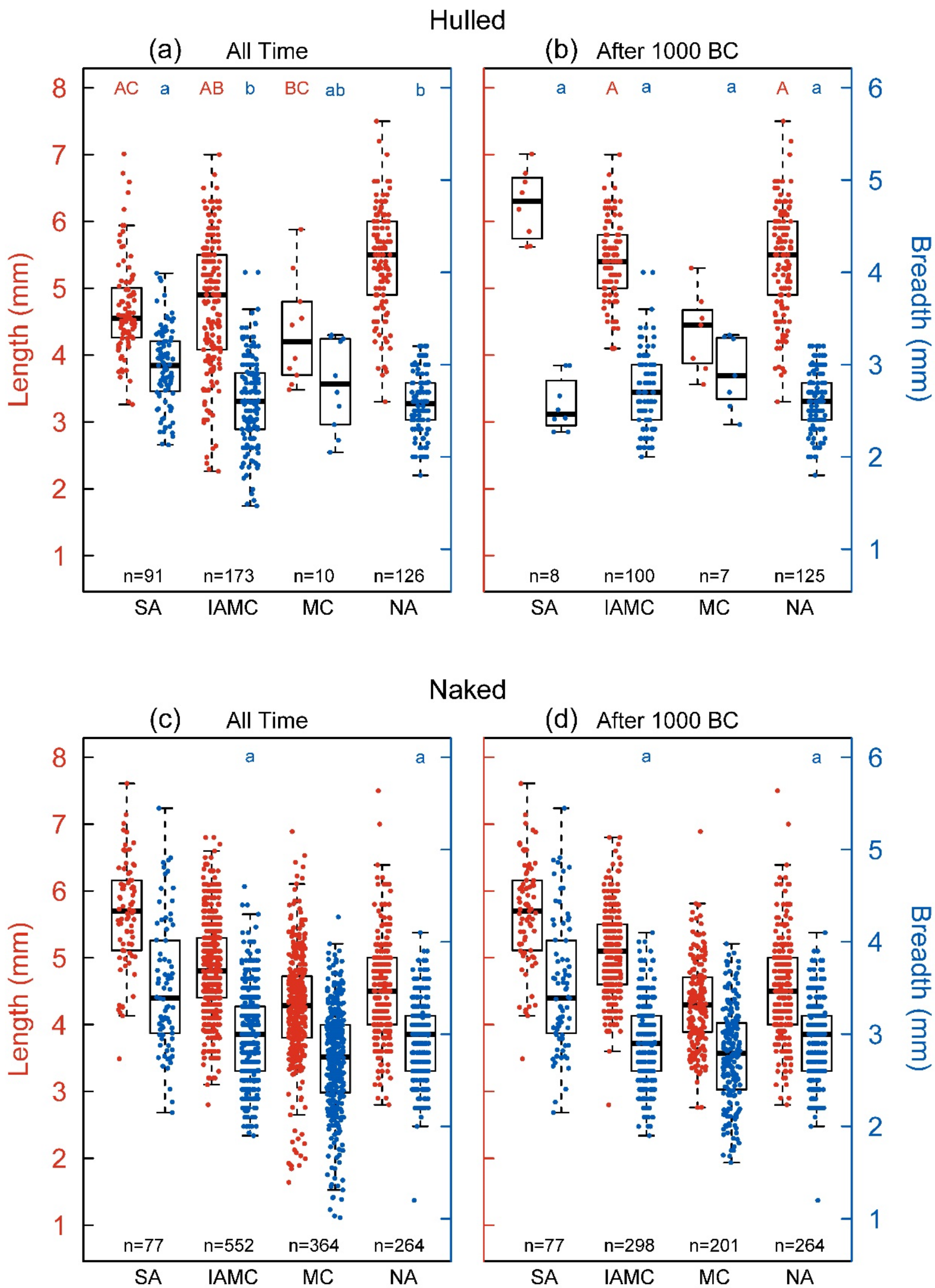

Figure 4. Boxplots of hulled All time (a) and hulled After 1000 BC (b), and naked All time (c) and naked After 1000 BC (d). Length measurements are visualized with the red boxplots and left y axis. Breadth measurements are visualized with blue boxplots and right y axis. Pairs of

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measurements are grouped by region: SA=South Asia, IAMC=Inner Asian Mountain Corridor, MC=Monsoonal China, NA=Northeast Asia. Non-significant statistical relationships share letters, all other relationships are significant, $p < 0.05$. Uppercase red letters represent length relationships and lowercase blue letters represent breadth relationships.

Discussion

The data presented here enable two inferences. The first relates to the geographical (and temporal) variation of barley grain size as it was dispersing eastwards. The second relates to barley's adaptation to high-altitude environments across the Tibetan Plateau. These inferences allow us to reflect on how culinary traditions were spread out geographically in the second/first millennium BC.

Grain size reduction as barley heads east

Our results show that the variation in barley grain sizes between the third millennium BC and the first millennium AD was primarily driven by regional differences. Generally the length (and to a certain extent breadth) of the grain measurements decreased from the West to the East (not including the more recent historical grains from Northeast Asia), with the shortest caryopses found in Monsoonal China, shorter than those in the IAMC and South Asia (Figure 2). This observation resonates with the pattern of archaeological free-threshing wheat previously documented, which also shows a west-to-east reduction (Liu et al. 2016). In other words, the sizes of both wheat and barley decreased during their eastward expansion.

The extremely reduced grain size is best accounted for by a distinct culinary tradition in Monsoonal China. As previously noted, societies in eastern and central China have employed (since the Neolithic until this day) cooking styles primarily oriented around boiling and steaming and whole-grain meal preparation. This culinary system favors smaller grain sizes, which are often accompanied by genetic mutations that cause amylose-low/free (sticky or glutinous) starch for higher cooking efficiency (e.g. Hunt et al. 2013; Fuller and Castillo 2016). It is worthy to note that prehistoric communities may not have considered *Triticum* and *Hordeum* varieties as separate crops. In the textual records dating to second/first millennium China, for example, the character *Mai* (麦) was used to denote wheat and barley collectively as it is used in modern Chinese today (Liu et al. 2017). Therefore, the selective constrains of food preparation practices

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could have applied uniformly across taxonomic differences as demonstrated by similar trends in *Triticum* and *Hordeum*. Our data suggest that selection for compact barley morphotypes was likely caused by modifications for the eastern cooking style.

Hulled, naked, two- and multiple row varieties

In addition, our data support previous observations of the preference for free-threshing grains in eastern Eurasia with naked barley being the almost exclusive type in Monsoonal China (Spengler 2015; Liu et al. 2017), hinting at a role of food preparation practice. Traditional farmers in Ethiopia, for example, often consider hulled barley less desirable as it is extremely time and labor intensive to process in domestic contexts, although it is less labor-intensive in the field and provides relatively higher grain yield than naked types (Asfaw 1999). However, the general trend of average grain size reduction as barley moved eastwards was not likely driven by the increase of hull-less grains in the East. When hulled and naked grains are considered separately, we see a strikingly similar pattern of west-to-east reduction for both groups (Figure 4). This indicates that they were subject to similar selective constraints that were relatively uniform across varietal and even taxonomic differences (considering the similar trend in *Triticum* (Liu et al. 2016).

The observed patterns should also be viewed in the context of needing to better understand grain morphology at the subspecies-level. It has been suggested that six-row barley (*H. vulgare* subsp. *vulgare* L.) tends to produce stubbier and plumper grains in contrast to the narrow and thinner two-row barley (*H. vulgare* subsp. *distichum* L.) (Ros et al. 2014; Fuller et al. 2017). As noted, two- and multi-row barleys were not separated in this study due to the lack of sufficient rachis information in many assemblages. In general, both six- and two-row barley were identified from sites along the IAMC. For example, Motuzaite Matuzeviciute and colleagues (2020b) report six- and two-row naked and hulled barleys from Chap I in Kyrgyzstan. In Kashmir, no rachis was recovered from Qasim Bagh, Pethpuran Teng and Kanispur, but Pokharia et al. (2017) noted twisted grains from Kanispur indicating multi-row barley. Archaeobotanical reports from China rarely discuss types of fertile florets and rachis evidence is limited. There are, however, a few visual reports of barley rachis internodes, including a six-row hulled form from Bangga in Tibet (Tang et al. 2021), six-row naked form from Dongtianshan (Tian et al. 2018), both six- and two-row rachises from Sidaogou (X. Liu unpublished data) in

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Xinjiang, and seemingly six-row hulled form from Xichengyi in Hexi Corridor (Fan 2016 master thesis).

In terms of the caryopsis shapes, Tian et al. (2021) noted that twisted barley grains are the main type in Adunqiaolu, western Xinjiang, indicating the predominance of multi-row. This is consistent with the observation at Bangga and Kaerdong in Tibet, although symmetric types are also present (Song et al. 2018; Tang et al. 2021). It is harder to evaluate barley types in Monsoonal China due to the lack of consistent rachis reporting. One of the coauthors (X. Liu) sorted through some of those assemblages in selecting specimens for radiocarbon and isotopic measurements (Liu et al. 2017) and noted both asymmetric and symmetric grains in those assemblages with a ratio significantly lower than 2:1 (a criteria commonly used to identify six-row barley). This perhaps indicates the coexistence of two- and multi-row barleys in prehistoric central China. Therefore, what the overall distribution of barley metrics suggests is that in addition to size reductions, there were also differences at the subspecies level. It is not easy, at this point, to evaluate the proportional contribution of multiple row types quantitively. Nevertheless, future investigations will clarify the regional variations among major varietal and subspecies differences.

Tibetan boiling-steaming free zone

Our results show the Tibetan grains, situated at the highest altitudes, are the largest across the regions. Recent whole-genome sequencing has indicated substantial gene flow in the past between high-altitude adapted wild barley and cultivated varieties on the Tibetan Plateau (Dai et al. 2012; Zeng et al. 2018) Although scholarship has hardly reached a consensus on the origin of Tibetan *H. spontaneum* (e.g. Lister et al. 2018; Zeng et al. 2018) such hybridization is thought to contribute to the altitudinal adaptation of modern naked barley (e.g.Zeng et al. 2018; Tang et al. 2021). The shortest barley grain at high altitudes (e.g. Haimenkou in Yunnan, Jinchankou in Qinghai, Shannashuzh in East Gansu, Chap II and Uch-Kurbu in Kyrgyzstan) in the third and second millennium BC can be understood in this context. This possibility resonates with the recent discussion of high-altitude adaptation of foxtail millet (*Setaria italica*) during the third/second millennium BC in eastern Tibetan Plateau that could have benefited from hybridization with cold-tolerant weedy relatives such as *S. viridis* (Song et al. 2021; Tang et al. 2021), Many cereal crops, including maize and finger millet show variations in morphotypes in

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the context of adaptation in a range of high- altitude environments, and our data adds to this growing literature (Goodman and Brown 1988; Asfaw 1999; Tsehaye et al. 2006).

Three of the largest average grain lengths are from sites in western Tibet (i.e. Dingdong, Bangga and Kaerdong). For example, at Dingdong, a site situated at c. 4000 m.a.s.l., average grain length and breadth are 6.25 ± 0.52 mm and 2.56 ± 0.29 mm, significantly larger than the grain metrics from sites in other regions. It is interesting to note that the barley from these sites are likely of the multi-row type (with both hulled and naked forms) as noted above. The distinct grain length is therefore not driven by the tallness of two-row type. Unlike cuisines in the rest of East Asia, Tibetan cuisine is characterized by its absence of boiling and steaming. This is due to the low vapor pressure at high elevations. The boiling point is about 86 °C at 4000 m.a.s.l., which makes boiling and steaming not only less efficient but also fuel demanding. Tibetan cuisine utilizes a grinding (without boiling) technique for a flour-based cereal cuisine – which is different from culinary traditions in either East Asia and eastern South Asia utilizing boiling-steaming and whole grain-based cuisine. The most prevailing staple in modern day Tibet, tsampa, is a roasted milled/ground barley flour-based meal, and ceramic vessels with boiling-and/or-steaming function are absent at sites in central and western Tibet (Tang et al. 2021).

Towards a complex culinary system in eastern Eurasia

In their insightful exploration of prehistoric culinary frontiers, Fuller and Rowlands (2011) depict a clear-cut boundary – correlating with the geographic limit of Asian summer monsoons – between the boiling and steaming traditions of East Asia (and eastern South Asia) and the grinding and baking traditions that originated in southwest Asia. This hypothesis is supported by the spread of *tabun*- and *firin*-type bread ovens originating with barley and wheat in Southwest Asian Pre-pottery Neolithic (Fuller and Carretero 2018) and the Neolithic Chinese ceramic tripod boiling (*Li/Ding/Guan*) and steaming (*Zeng/Yan*) kits across eastern Asia (Makibayashi 2008, 2014; Fuller and Rowlands 2011). Central Asia, including the Inner Asia Mountains and Tibetan Plateau, is placed in the grinding-and-baking zone (Fuller and Rowlands 2011). However, the Bronze Age eastern Central Asian cuisines were likely more complex than previously assumed with boiling technology integrated with the grinding and baking tradition. This culinary complexity can be supported by the varied material assemblage from the region, including stone querns, mudbrick ovens, and ceramic vessels with boiling function (Spengler, Frachetti, and Domani 2014; Rouse et

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al. 2019; Motuzaite Matuzeviciute et al. 2020a). However, the vessels used for boiling emerged from a distinct tradition than the eastern tripod-boiling artefacts that are prevalent in the Neolithic and Bronze Age China (Makibayashi 2008; Han 2017) The eastern Central Asian boiling tradition is materially manifested by a type of round bottomed pottery vessel with multiple functions that includes boiling which is prevalent across Central Asia (Han 2017). This typology was probably rooted further west in cultures dated between sixth and fourth millennium BC. Lipid-reside from Botai in Northern Kazakhstan indicates dairying within ceramic vessels, which is likely connected with dairy-based culinary practices further west (Outram et al. 2012). In the second millennium BC, the round-bottomed vessels further developed into several regionally typological groups in the IAMC including the Tianshan, Altai region and the Hexi corridor, and could be used in multiple food preparation practices involving boiling (Han 2017).

It is not unreasonable to speculate that grains like barley were boiled in such vessels as a stew-type meal along with meat, diary, grains, vegetables, and spices. Such a cuisine is still favorable in this part of the world (Bacon 1954; Mack and Surina 2005; McLean 2012). In the medium of a stew, with the intensive cooking energy required for tenderizing meat, the size of grain would not be of primary importance. Different sized grains, including the routinely found compact forms in the IAMC (e.g. Spengler, Frachetti, and Domani 2014; Spengler 2015; Motuzaite-Matuzeviciute et al. 2018, 2020ab), would then be useful for both boiling and baking recipes. This is dissimilar to the eastern Chinese whole grain boiling-steaming traditions, where small grains are important for an efficient cooking of the desired porridge dish. This speculation can be further supported by the isotopic evidence for relatively high animal protein/dairy consumption in this region (Wang et al. 2019; Liu and Reid 2020). The emerging picture suggests at least three culinary traditions co-existing in the eastern part of Eurasia during the second and first millennium BC: steaming-boiling whole grain tradition in Monsoonal China, boiling-free flour-based cuisine in Tibetan Plateau and a mix of cooking across the boiling-grinding-baking spectrum in the IAMC. Our data support this hypothesis of a more complex system of eastern Eurasian cuisines fairly well (Figure 5) and prompts further investigations into the deep-seated culinary traditions in the IAMC and Tibetan Plateau.

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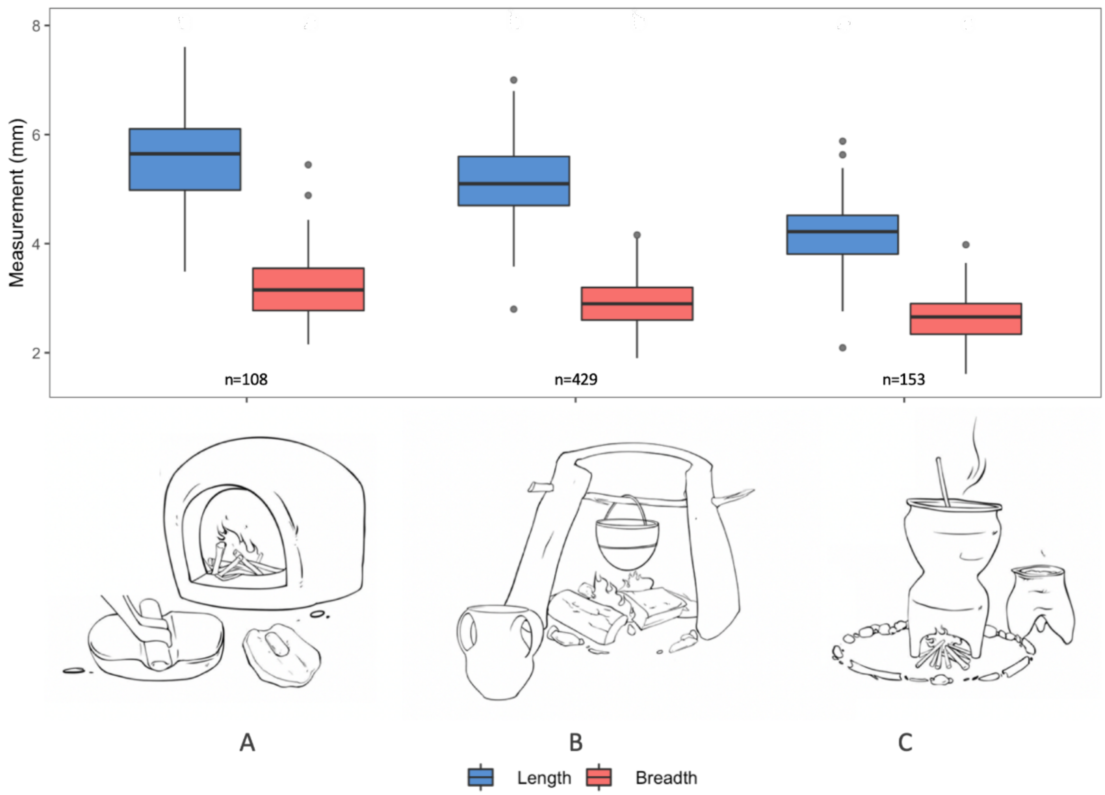

Figure 5. Length of barley grains from three hypothetical culinary zones in the first millennium BC: A) Tibetan Plateau boiling -and steaming-free zone with grinding and oven-baking, B) a mix of grinding, baking, and boiling in Inner Asian Mountain Corridor using multi-function oven for boiling and baking, and C) Monsoonal China boiling and steaming zone using tripod boiling vessels. All length relationships (blue) and breadth relationships (red) are pronounced, $p<0.05$.

Conclusion

In this paper, we consider barley grain size and morphotype in the context of its eastern movement across Asia in association with culinary preference. Our results allow for three inferences concerning culinary practices and barley phenotypes. First, we find barley diminished in size as it moved from its origin in southwestern Asia to Central and East Asia between the 3rd and 1st millennium BC. In particular, barley grains in Monsoonal China became greatly reduced in comparison to other regions as the crop was incorporated into eastern small grain cuisines. The reverse pattern is observed in the high-altitude Tibetan environment, which is attributed to the practicalities of cooking under low vapor pressure conditions. Second, our results infer a complex culinary system in eastern Eurasia with the coexisting of three cooking traditions that

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have not been previously documented. Third, we draw attention to the value of recording rachis and caryopsis evidence in future research to distinguish two- and multiple-row barley and to better understand barley phenotypes at the subspecies-level.

Together with previously published grain metrics of free-threshing wheat (Liu et al. 2016), our findings raise awareness of the geographic decoupling of grains and cuisines in the context of prehistoric food globalization, such that wheat and barley travelled into eastern and central China during the second and first millennium BC, but the grain morphotypes and the western grinding-and-baking cuisines did not. These results resonate with the recent discussion of the disaggregation of the eastern Neolithic grains and their associated culinary approach: millet grains moved westwards along the Hexi and Inner Asian Mountain Corridor and beyond even though their sticky genotypes did not (Hunt et al. 2013, Hunt et al. in prep.). Our results further question the role of grain size in measuring the domestication process and infer the transcontinental nature of domestication itself.

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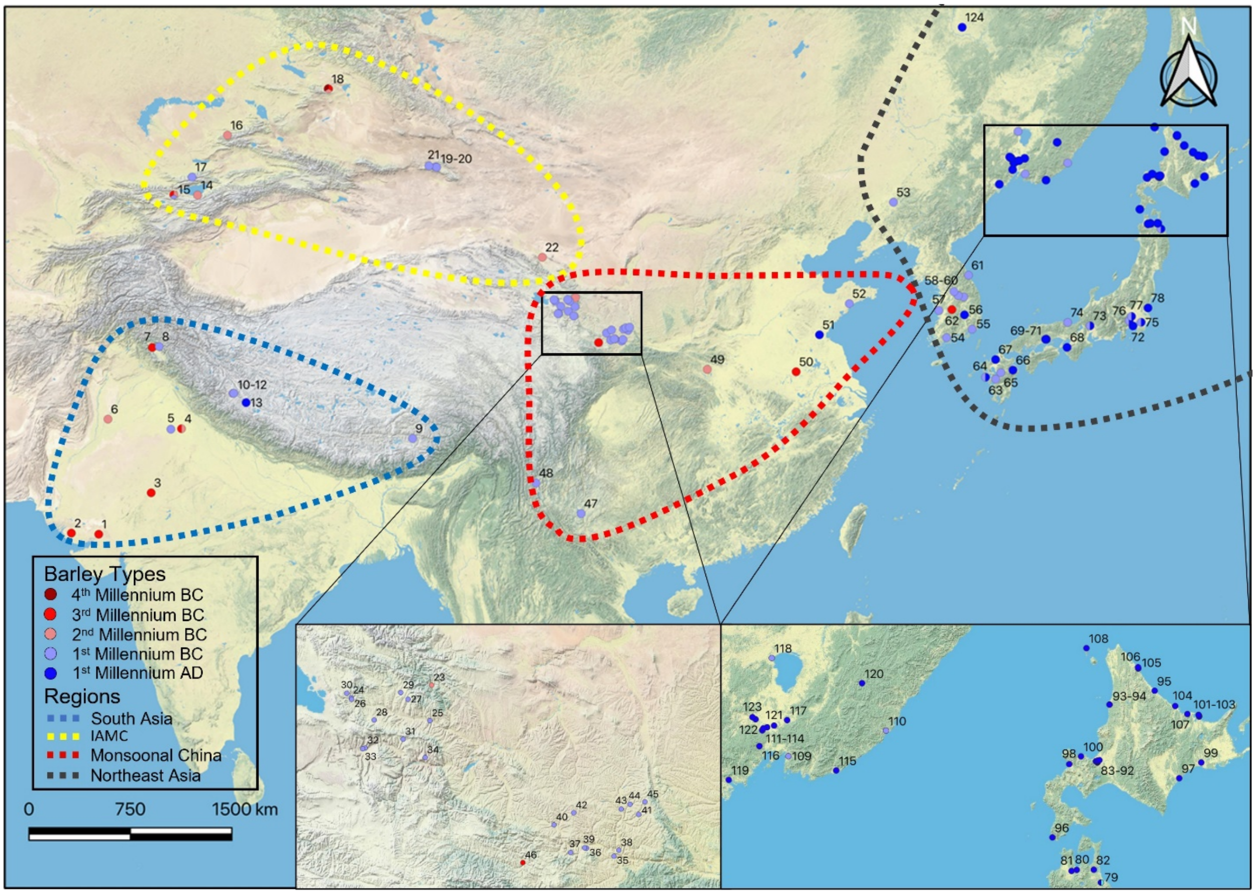
Supplementary Data



Supplementary Figure 1. Map of sites where barley grains are analyzed by time period. Regional categories are superimposed. Time periods (millennia) are represented by colored circles. Sites are numbered and referenced in **Error! Reference source not found.**.

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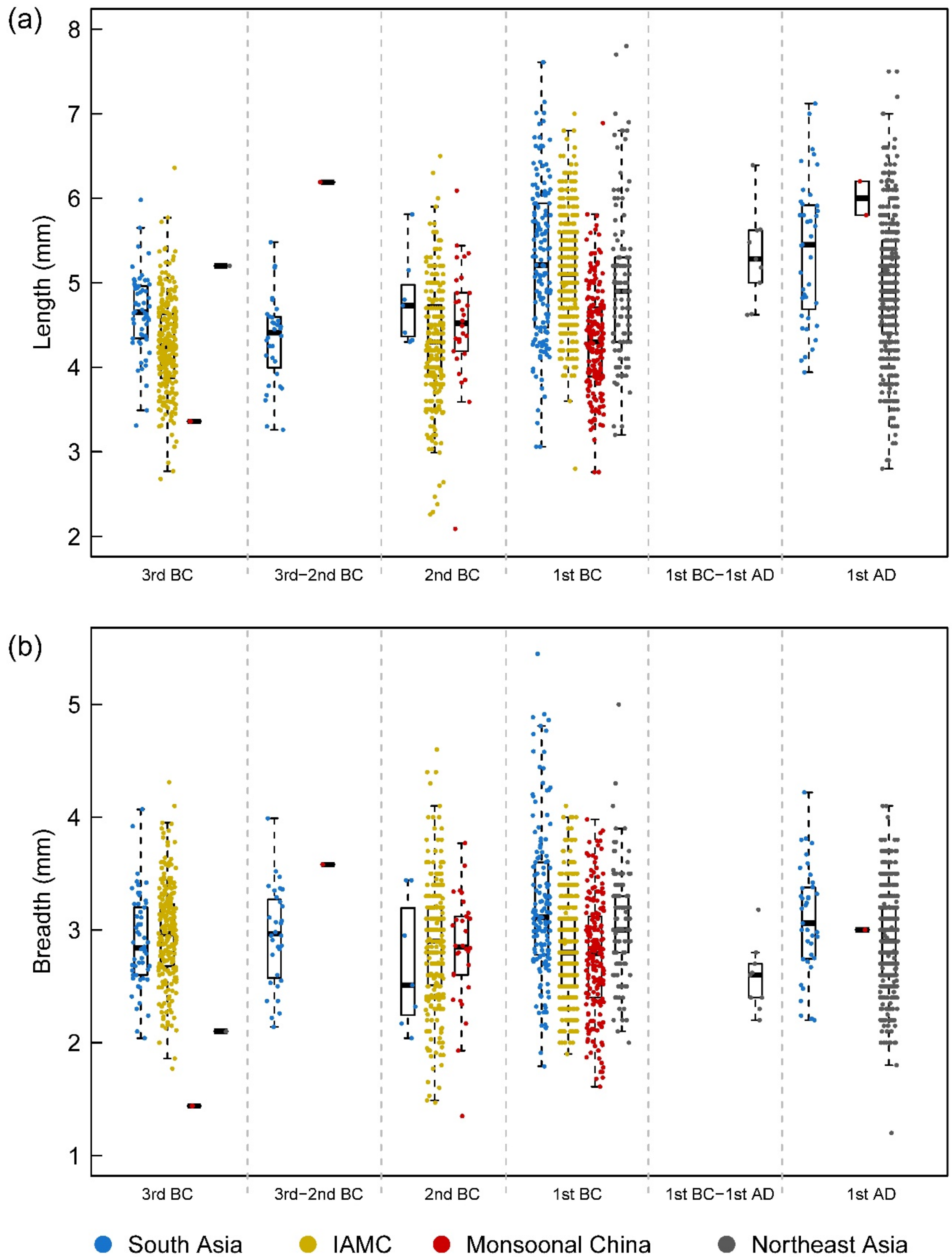

Supplementary Figure 2. Scatterplot of raw grain length data per region through time, (a) length and (b) breadth. Regional data grouped by color from left to right: blue South Asia, yellow IAMC, red Monsoonal China, grey Northeast Asia. Raw data, includes both individual measurements and averages.

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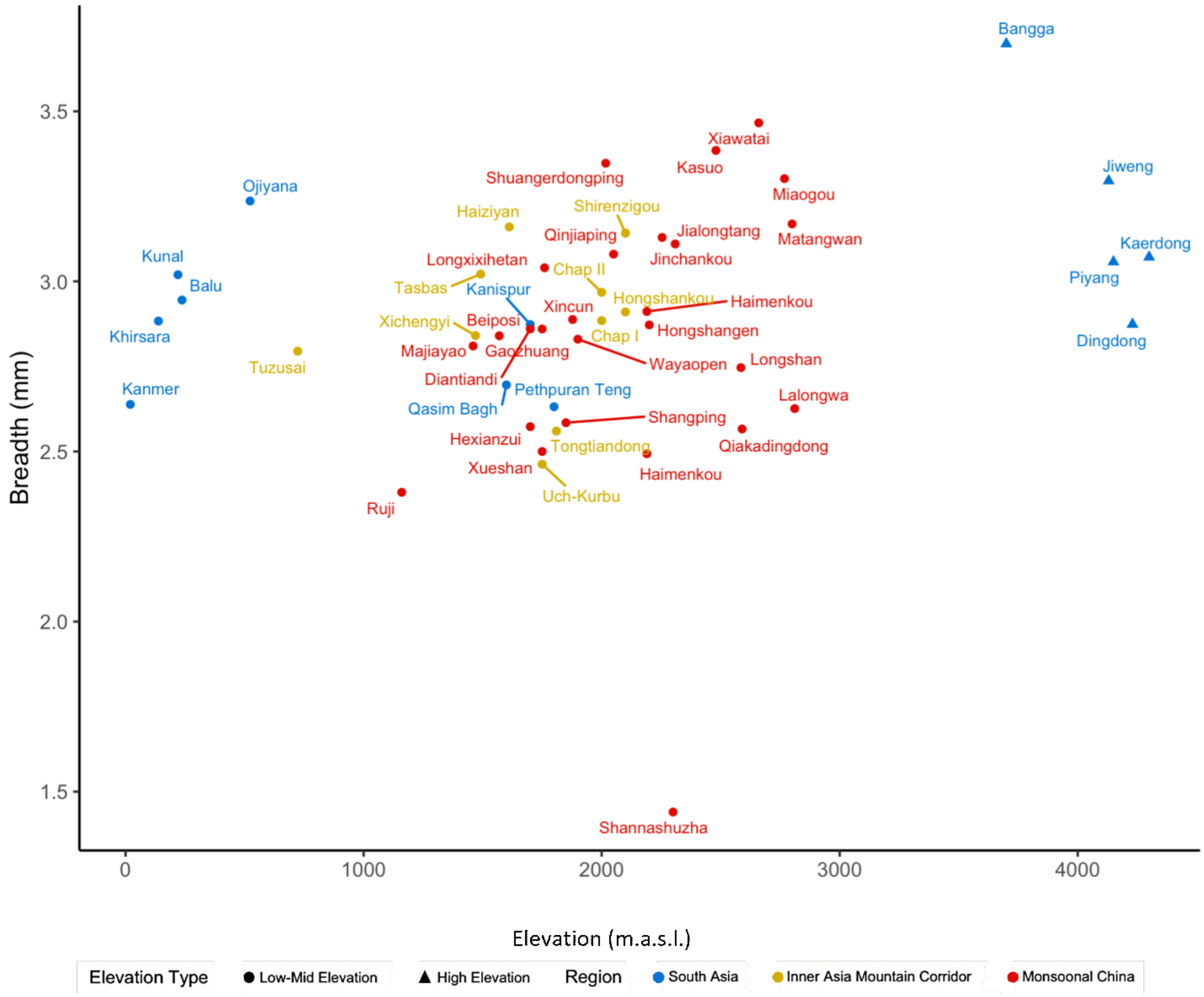

Supplementary Figure 3. Scatterplot of relationship of averaged grain breadth from all sites (excluding Northeast Asia), y-axis, and elevation of sites, x-axis. Sites are colored representing region, and points represent low-mid elevation and high elevation.

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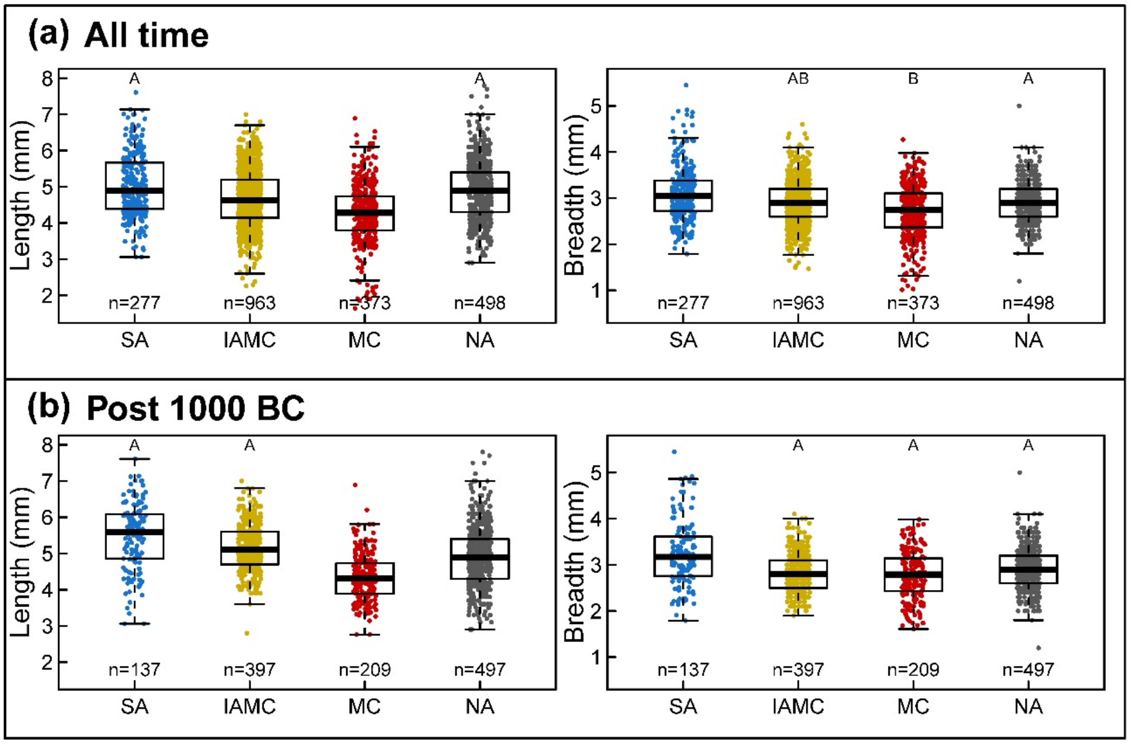

Supplementary Figure 4. Boxplots of only reported single grain barley measurements: (a) from all times periods, (b) from after 1000 BC. Length measurements are on the left and breadth measurements are on the right. Nonsignificant relationships share letters, all other relationships are significant, $p<0.05$

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Supplementary Table 1. Summary of barley grain measurements from South Asia, IAMC, Monsoonal China and Northeast Asia. Site numbers coincide with labelled points in Figure 1. Measurements represent the mean length, breadth and height of grains in mm, with standard deviation (1σ), based on the number, n, of studied grains from each site. X marks type of grain, but unknown number.

Region	Site	Millennium (BC/AD)	Elevation masl	Length	Breadth	Height	L/B Ratio	Single / Average	Hulled	Naked	both	unkown	n	Source
Gujarat, India (South Asia)	Kanmer (1)	3rd BC	20	4.9 ± 0.1	2.6 ± 0.3	1.7 ± 0.1	1.9	Single				6	6	This study, Pokharia, A. et al,. 2011
	Khirsara (2)	3rd BC	138	4.7 ± 0.2	2.9 ± 0.4	1.7 ± 0.1	1.6	Single				6	6	This study, Pokharia, A. et al,. 2017
	Ojiyana (3)	3rd BC	523	4.9 ± 0.3	3.2 ± 0.3	1.7 ± 0.1	1.5	Single	8				8	This study, Pokharia, A., 2008
Haryana, India (South Asia)	Balu (4)	3rd-2nd BC	237	4.3 ± 0.5	3.0 ± 0.4	1.7 ± 0.2	1.5	Single	32				32	This study, Saraswat, K., & A. Pokharia, 2002
	Kunal (5)	1st BC	220	4.7 ± 0.5	3.0 ± 0.4	1.6 ± 0.2	1.5	Single	43				43	This study, Saraswat, K., & A. Pokharia, 2002
Kashmir (South Asia)	Qasim Bagh (6)	2nd BC	1600	4.8 ± 0.5	2.69 ± 0.59	2.1 ± 0.4	1.8	Single	7				7	This study
	Kanispur (7)	3rd BC	1700	4.5 ± 0.5	2.8 ± 0.4	2.0 ± 0.3	1.5	Single			38		38	This study, Pokharia, A. et al., 2018
	Pethpuran Teng (8)	1st BC		4.1 ± 0.8	2.6 ± 0.5	1.9 ± 0.3	1.6	Single	13				13	This study
Tibet, China (South Asia)	Bangaa (9)	1st BC	3500	6.0 ± 0.8	3.7 ± 0.8	2.8 ± 0.7	1.6	Single		51			51	This study
	Piyang (10)	1st BC	4150	4.6 ± 0.5	3.0 ± 0.4	2.1 ± 0.2	1.5	Single		7			7	This study
	Jiweng (11)	1st BC	4130	5.2 ± 0.5	3.3 ± 0.3	2.5 ± 0.2	1.6	Single		9			9	This study
	Dingdong (12)	1st BC	4230	6.3 ± 0.5	2.6 ± 0.3	1.8 ± 0.2	2.4	Single	8	10			18	This study
	Kaerdong (13)	1st AD	4300	5.4 ± 0.8	3.1 ± 0.5		1.8	Single			39		39	Song, J. et al., 2018
Kyrgyzstan (IAMC)	Uch-Kurbu (14)	2nd BC	1750	3.9 ± 0.7	2.5 ± 0.5	2.0 ± 0.4	1.6	Single	72				72	Motuzaite Matuzeviciute, G. et al,. 2018
	Chap I (15)	late 2nd - early 1st BC	2000	5.2 ± 0.6	2.9 ± 0.5	2.2 ± 0.3	1.8	Single	100	200			300	Motuzaite Matuzeviciute, G., 2020b, 2021ab
	Chap II (15)	3rd BC	2000	4.3 ± 0.6	3.0 ± 0.4	2.3 ± 0.3	1.4	Single				240	240	Motuzaite Matuzeviciute, G., 2020a
Kazakhstan (IAMC)	Tasbas (16)	2nd BC	1492	4.5 ± 0.6	3.0 ± 0.5		1.5	Single		207			207	Spengler, R., 2013
	Tuzusai (17)	1st BC	723	5.0 ± 0.7	2.8 ± 0.4		1.8	Single		95			95	Spengler, R., 2013
Xinjiang, China (IAMC)	Tongtian Cave (18)	4th-2nd BC	1810	4.2	2.6	1.9	1.6	Average		X				Zhou, X. et al., 2020
	Shirenzigou (19)	1st BC	2100	5.0 ± 0.0	3.0 ± 0.2	2.2 ± 0.2	1.6	Single		2			2	Tian, D., 2018
	Shirenzigou (19)	unknown	2100	5.0 ± 0.7	3.2 ± 0.5	2.4 ± 0.4	1.6	Single		30			30	Tian, D., 2018
	Hongshankou (20)	1st BC	2100	4.8	2.9	2.1	1.6	Single		1			1	Tian, D., 2018
	Haiziyan (21)	unknown	1612	4.9	3.2	2.3	1.5	Single		1			1	Tian, D., 2018
West Gansu, China (IAMC)	Xichengyi (22)	2nd BC	1470	4.7 ± 0.6	2.8 ± 0.6	2.0 ± 0.4	1.6	Single		15			15	Fan, X., 2016
Qinghai (Monsoonal China)	Jinchankou (23)	2nd BC	2299	4.8 ± 0.5	3.0 ± 0.3	2.4 ± 0.7	1.6	Single		6			6	Yang, 2014
	Miaogou (24)	1st BC	2768	5.0 ± 0.8	3.3 ± 0.4	2.5 ± 0.4	1.5	Single		10			10	This study
	Shuangerdongping (25)	1st BC	2017	4.6 ± 0.8	3.4 ± 0.4	2.4 ± 0.3	1.4	Single		11			11	This study
	Longshan (26)	1st BC	2585	4.0 ± 0.4	2.8 ± 0.4	2.1 ± 0.3	1.5	Single		11			11	This study
	Xiawatai (27)	1st BC	2660	4.6 ± 0.3	3.5 ± 0.2	2.4 ± 0.4	1.3	Single		5			5	This study
	Kasuo (28)	1st BC	2480	5.0 ± 0.6	3.4 ± 0.3	2.5 ± 0.3	1.5	Single		10			10	This study
	Qiakadingdong (29)	1st BC	2590	4.7 ± 0.4	2.6 ± 0.4	2.0 ± 0.6	1.8	Single		5			5	This study
	Matangwan (30)	unknown, likely 1st BC	2888	5.2 ± 0.9	3.2 ± 0.6	2.3 ± 0.3	1.6	Single		9			9	This study
	Lalongwa (31)	1st BC	2811	3.8 ± 0.3	2.6 ± 0.5	1.8 ± 0.5	1.4	Single		5			5	This study
	Hongshangen (32)	unknown, likely 1st BC	3000	5.0 ± 0.3	2.9 ± 0.4	2.3 ± 0.2	1.7	Single		10			10	This study
	Jialongtang (33)	1st BC	2254	4.9 ± 0.5	3.1 ± 0.4	2.4 ± 0.3	1.6	Single		10			10	This study
	Xincun (34)	1st BC	1878	4.4 ± 0.2	2.9 ± 0.4	2.1 ± 0.2	1.5	Single		5			5	This study
East Gansu (Monsoonal China)	Majiayao (35)	1st BC	1460	4.3 ± 0.5	2.8 ± 0.4		1.6	Single		15			15	Chen T., 2020
	Diantiandi (36)	1st BC		4.3 ± 0.5	2.9 ± 0.5		1.5	Single		24			24	Li, H., 2018
	Wayaopen (37)	1st BC	1850	4.8 ± 0.9	2.8 ± 0.6		1.7	Single		16			16	Chen T., 2020
	Ruji (38)	1st BC	1160	3.6 ± 0.4	2.4 ± 0.3		1.5	Single		26			26	Chen T., 2020
	Beiposi (39)	1st BC	1570	4.9 ± 0.9	2.8 ± 0.4		1.7	Single		13			13	Chen T., 2020
	Longxixihetan (40)	1st BC	1760	4.3 ± 0.5	2.8 ± 0.4		1.6	Single		15			15	Chen T., 2020
	Hexianzui (41)	1st BC	1700	4.0 ± 0.6	2.6 ± 0.4	2.1 ± 0.3	1.6	Single		9			9	Li, H., 2018
	Hexianzui H1 (41)	1st BC	1700	4.2	2.7	2.1	1.6	Average		X				Li, H., 2018
	Qinjiaping (42)	1st BC	2050	4.1 ± 0.6	3.1 ± 0.4		1.3	Single		8			8	Chen T., 2020
	Sanjiaodi (43)	1st BC	1700	2.1 ± 0.3	1.4 ± 0.2		1.5	Single		16			16	Chen T., 2020
	Gaozhuang (44)	1st BC	1750	4.6	2.9	2.0	1.6	Average		X				Li, H., 2018
	Shangping (45)	1st BC	1850	4.2 ± 0.5	2.6 ± 0.5	1.9 ± 0.4	1.6	Single		118			118	Li, H., 2018
	Shannashuzha (46)	3rd BC	2300	3.4	1.4	1.4	2.4	Single		1			1	Hu, Z., 2015
Yunnan (Monsoonal China)	Xueshan (47)	1st BC		5.2	2.5		2.1	Average						Wang, Q. et al., 2019
	Haimenkou (48)	1st BC		4.3 ± 0.6	2.9 ± 0.4		1.5	Single	13				13	Xue, Y., 2010
	Haimenkou (48)	2nd BC		4.4 ± 1.3	2.5 ± 0.7		1.7	Single	X					Xue, Y., 2010
Henan (Monsoonal China)	Shengmingpu (49)	1st BC	160	3.9 ± 1.0	3.1 ± 0.8			Single				2	2	Liu, H. et al., 2017
Anhui (Monsoonal China)	Yuhui (50)	3rd BC	19	6.2	3.6	2.1	1.7	Average		X				Yin, D., 2013
Shandong (Monsoonal China)	Dongpan (51)	1st AD	2	6.0 ± 0.3	3.0		2.0	Single				2	2	Wang, H. et al., 2011
	Beiqian 2007 (52)	1st BC	2	4.7	2.9	2.3	1.6	Average		X			7	Jin, G. et al., 2013
	Beiqian 2007-2013 (52)	1st BC	2	4.6	2.7	2.3	1.7	Average		X				Wei, N., 2018
Liaoning (Monsoonal China)	Qingzhuangzi (53)	1st BC	60	4.0	3.4		1.2	Average		X			17	Liu, X., & Y. Sun, 2019
South Korea (Northeast Asia)	Geumpyeong(54)	1st BC	5	6.7	3.4		2.0	Single				1	1	Kobata, H., 2011
	Buwon-dong (55)	1st BC	10	4.5 ± 0.9	2.7 ± 0.4		1.7	Single		10			10	Kobata, H., 2011
	Chilgok (56)	1st AD	100	5.2	3.3		1.6	Average				X		Kobata, H., 2011
	Pyeongra-ri (57)	1st BC	100	5.4 ± 0.8	3.1 ± 0.4		1.7	Single	1	12			13	Kobata, H., 2011
	Suyanggae (58)	1st BC	145	5.9 ± 0.9	3.7 ± 0.6		1.4	Single				2	2	Kobata, H., 2011
	Jodong-ri (59)	1st BC	75	6.2 ± 0.6	3.0 ± 0.1		2.1	Single				5	5	Kobata, H., 2011
	Heunam-ri (60)	1st BC	73	7.4 ± 0.6	3.3 ± 0.4		2.3	Single				2	2	Kobata, H., 2011
	Gapyeong-ri (61)	1st BC	5	5.0	3.0		1.7	Average				X		Kobata, H., 2011
	Daecheon-ri (62)	3rd BC	140	5.2	2.1		2.5	Single	1				1	Kobata, H., 2011
Kyushu, Japan (Northeast Asia)	Uenohara (63)	1st BC		3.8	2.0		1.9	Average				X		Kobata, H., 2011
	Wakamisaki (64)	1st BC-1st AD		4.6	2.2		2.1	Average				X		Kobata, H., 2011
	Ishinohon (65)	1st BC		3.8	2.2		1.7	Average	X					Kobata, H., 2011
	Maeda (66)	1st AD		5.8 ± 0.1	3.0 ± 0.6	2.0 ± 0.4	1.9	Single				3	3	Niiyama, M., 2005
	Morooka (67)	1st AD	9	5.5 ± 0.6	2.4 ± 0.4	2.3 ± 0.4	2.3	Single	20	1			21	Kobata, H., 2011
Honshu, Japan (Northeast Asia)	Ota-Kuroda (68)	1st AD		6.2	3.1		2.0	Average	X					Kobata, H., 2011
	Tsudera (69)	1st AD		5.3	3.0		1.8	Average	X					Kobata, H., 2011
	Tatatsuka (70)	1st BC-1st AD		5.3	2.7		2.0	Average	X					Kobata, H., 2011
	Shikatacho (71)	1st AD	2	5.7 ± 0.1	2.9 ± 0.2		2.0	Single	1	2			3	Kobata, H., 2011
	The 2nd Yokohama city road No. 6 (72)	1st AD		5.9 ± 1.2	2.7 ± 0.6	2.2 ± 0.3	2.2	Single	7	3			10	Yokohama City, 1981
	Nishinosho (73)	1st BC-1st AD	10	4.6	2.6		1.8	Average	X					Kobata, H., 2011
	Kuwagaishimo (74)	1st BC	10	5.2 ± 0.3	3.0 ± 0.6		1.8	Single				2	2	Kobata, H., 2011
	Shimokitahara (75)	1st BC-1st AD		6.4	3.2		2.0	Average		X				Kobata, H., 2011
	Nakano Konohara (76)	1st AD		3.3	3.1	1.1	1.1	Average	X					Kasahara et al., 1987
	Tokyo Kanohara (76)	1st BC-1st AD	135	5.2	2.8		1.9	Average	X					Kobata, H., 2011
	Kawagoe (77)	1st BC-1st AD		5.0	2.3		2.2	Average		X				Kobata, H., 2011
	Takanosu (78)	1st AD		4.8	2.6	1.9	1.8	Average				X		Hitachinaka City, 2013
	Yawata (79)	1st BC-1st AD		5.6	2.6		2.1	Average		X				Kobata, H., 2011
	Nogi (80)	1st AD		5.8 ± 0.5	2.5 ± 0.2	1.9 ± 0.2	2.3	Single	50				50	Leipe C., et al. 2017
	Takayashikidate (81)	1st AD		5.7 ± 0.3	2.6 ± 0.2	2.1 ± 0.4	2.2	Single	7				7	Leipe C., et al. 2017
	Uc+B2:B89hiebizawa (82)	1st AD		5.9 ± 1.1	2.7 ± 0.28	2.3 ± 2.8	2.2	Single	2				2	Leipe C., et al. 2017

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Supplementary Table 1 continued: Summary of barley grain measurements.

Region	Site	Millennium (BC/AD)	Elevation masl	Length	Breadth	Height	L/B Ratio	Single / Average	Hulled	Naked	both	unkown	n	Source
Hokkaido, Japan (Northeast As	K39-Haseko site (83)	1st AD		4.7	2.4	1.6	2.0	Average				X		Yamada, G., 2005
	K39-Ryokka site (84)	1st AD		6.2	2.4	1.8	2.6	Average	X					Yamada, G., 2005
	K39-the 6th survey (85)	1st AD		5.3	2.5	2.1	2.1	Average	X					Yamada, G., 2005
	K39-the 7th survey (86)	1st AD		5.7	2.4	1.7	2.4	Average	X					Yamada, G., 2005
	K435 (87)	1st AD		4.9	2.4	1.7	2.0	Average		X				Yamada, G., 2005
	K440 (88)	1st AD		4.3	2.7	2.8	1.6	Average	X					Yamada, G., 2005
	K441-North 33 (89)	1st AD		5.2	3.2	2.1	1.6	Average		X				Yamada, G., 2005
	H317 (90)	1st AD		5.7	2.3	1.8	2.4	Average	X					Yamada, G., 2005
	K441-North 34 (91)	1st AD		4.0	2.8	2.2	1.4	Average		X				Yamada, G., 2005
	Sakshkotni River (92)	1st AD		5.3	2.4	1.8	2.2	Average	X					Yamada, G., 2005
	Kagawa 6 (93)	1st AD		4.9	3.1	2.5	1.6	Average	X					Yamada, G., 2005
	Kagawa Line 3 (94)	1st AD		5.1	3.8	2.9	1.3	Average		X				Yamada, G., 2005
	Oumu (95)	1st AD	6	4.5 ± 0.4	3.3 ± 0.3	2.5 ± 0.2	1.4	Single			X			Yamada, G., 2005
	Satsumae (96)	1st AD		5.0	2.7	2.3	1.9	Average	X					Yamada, G., 2005
	Tokachitai Wakatsuki (97)	1st AD	15	4.8	3.0	2.4	1.6	Average	x					Yamada, G., 2005
	Herokaruusu (98)	1st AD		5.3	2.4	1.8	2.2	Average		X				Leipe C., et al. 2017
	Hokuto (99)	1st AD		4.6	3.2	2.3	1.4	Average				X		Yamada, G., 2005
	Rashima C (100)	1st AD	69	6.1	3.0		2.0	Average		X				Leipe C., et al. 2017
	Moyoro (101)	1st AD	10	3.8	2.7	2.0	1.4	Average	X					Yamada, G., 2005
	Nitsuiwa (102)	1st AD	1	4.3	2.9	2.4	1.5	Average	X					Yamada, G., 2005
	Futatsuiwa (103)	1st AD		4.3 ± 0.3	2.9 ± 0.2		1.5	Single	15				15	Leipe C., et al. 2017
	Kawanishi (104)	1st AD	5	4.2	2.7	2.5	1.6	Average		X				Leipe C., et al. 2017
	Ochikire River Left Bank (105)	1st AD	145	5.1	3.1	2.0	1.6	Average	X					Yamada, G., 2010
	Menashidomari (106)	1st AD	15	4.5 ± 0.5	3.0 ± 0.3		1.5	Single		10			10	Leipe C., et al. 2017
	Hamasaroma (107)	1st AD	35	4.4	2.8	2.0	1.6	Average	X					Leipe C., et al. 2017
	Hamanaka 2 (108)	1st AD		4.1 ± 0.6	3.0 ± 0.4	2.3 ± 0.3	1.4	Single		87			87	Leipe C., et al. 2017
Primorye, Russia (Northeast A	Malaya Podushechka (109)	1st BC		4.6 ± 0.4	2.8 ± 0.4	2.2 ± 0.3	1.6	Single		26			26	Leipe C., et al. 2017
	Sinie Skaly (110)	1st BC		5.2 ± 0.5	3.3 ± 0.4	2.4 ± 0.3	1.6	Single		10			20	Leipe C., et al. 2017
	Krounovka I (111)	1st BC		4.5 ± 0.5	3.1 ± 0.4	2.3 ± 0.3	1.4	Single		13			13	Leipe C., et al. 2017
	Abricosovskoe (112)	1st AD		5.4 ± 0.7	2.9 ± 0.5	2.7 ± 0.3	1.8	Single		4			4	Leipe C., et al. 2017
	Korsakovskoe (113)	1st AD		4.0 ± 0.7	2.6 ± 0.6	2.1 ± 0.4	1.6	Single		8			8	Leipe C., et al. 2017
	Borisovka-3 (114)	1st AD		2.8	2.2		1.3	Single		1			1	Leipe C., et al. 2017
	Shelomaev Kulch (115)	1st AD		4.9 ± 0.4	2.9 ± 0.2	2.0 ± 0.2	1.7	Single		11			11	Leipe C., et al. 2017
	Anan'evskoe (116)	1st AD		5.1 ± 0.5	3.1 ± 0.4	2.4 ± 0.3	1.6	Single				65	65	Leipe C., et al. 2017
	Gorbatka (117)	1st AD		5.3 ± 0.7	3.2 ± 0.5	2.5 ± 0.3	1.6	Single				8	8	Leipe C., et al. 2017
	Semipiatnaya I (118)	1st BC		4.2 ± 0.5	2.9 ± 0.2	2.3 ± 0.3	1.5	Single		15			15	Leipe C., et al. 2017
	Kraskinskoe 2 (119)	1st AD		4.2	2.5	1.8	1.7	Average		X				Leipe C., et al. 2017
	Koksharovskoe-1 (120)	1st AD		4.8 ± 0.8	2.9 ± 0.5	2.2 ± 0.6	1.7	Single		6			6	Leipe C., et al. 2017
	Izvestkovaya Sopka (121)	1st AD		5.2 ± 0.5	3.1 ± 0.4	2.5 ± 0.3	1.7	Single				60	60	Leipe C., et al. 2017
	Chernyatino-5 (122)	1st AD		4.4 ± 0.4	2.7 ± 0.3	2.0 ± 0.3	1.7	Single				18	18	Leipe C., et al. 2017
	Konstantinovskoe (123)	1st AD		4.9	3.2	2.6	1.5	Average		X				Leipe C., et al. 2017
Amur Oblast, Russia (Northeas	Osinovoe Ozero (124)	1st AD		4.9 ± 0.6	3.2 ± 0.7	2.5 ± 0.6	1.6	Single		4			4	Leipe C., et al. 2017

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Supplementary Table 2. Statistical results of temporal and regional grain measurements by All Time and After 1000 BC.

Length All Time				
Kruskal-Wallis	chi-squared	Df	p-value	n
	171.89	3	2.20E-16	2075
Multiple comparison test after Kruskal-Wallis			P-value 0.05	
Comparisons		obs.dif	critical.dif	dif
IAMC-Monsoonal China		295.5928	100.67627	TRUE
IAMC-Northeast Asia		201.81642	88.20663	TRUE
IAMC-South Asia		225.24708	112.99063	TRUE
Monsoonal China-Northeast Asia		497.40922	110.55041	TRUE
Monsoonal China-South Asia		520.83988	131.17875	TRUE
Northeast Asia-South Asia		23.43066	121.8711	FALSE
Breadth All Time				
Kruskal-Wallis	chi-squared	Df	p-value	n
	55.586	3	5.15E-12	2176
Multiple comparison test after Kruskal-Wallis			P-value 0.05	
Comparisons		obs.dif	critical.dif	dif
IAMC-Monsoonal China		186.60092	100.67627	TRUE
IAMC-Northeast Asia		14.44145	88.20663	FALSE
IAMC-South Asia		177.8337	112.99063	TRUE
Monsoonal China-Northeast Asia		201.04237	110.55041	TRUE
Monsoonal China-South Asia		364.43462	131.17875	TRUE
Northeast Asia-South Asia		163.39225	121.8711	TRUE

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Supplementary Table 3 continued: Statistical results of temporal and regional grain measurements by All Time and After 1000 BC.

Length after 1000 BC				
Kruskal-Wallis	chi-squared	Df	p-value<	n
	206.95	3	2.20E-16	1302
Multiple comparison test after Kruskal-Wallis		P-value 0.05		
Comparisons		obs.dif	critical.dif	dif
IAMC-Monsoonal China		397.5396	84.47537	TRUE
IAMC-Northeast Asia		112.054	65.13276	TRUE
IAMC-South Asia		117.7738	98.26057	TRUE
Monsoonal China-Northeast Asia		285.4855	80.20903	TRUE
Monsoonal China-South Asia		515.3133	108.84095	TRUE
Northeast Asia-South Asia		229.8278	94.61787	TRUE
Breadth after 1000 BC				
Kruskal-Wallis	chi-squared	Df	p-value<	n
	48.975	3	1.32E-10	1302
Multiple comparison test after Kruskal-Wallis		P-value 0.05		
Comparisons		obs.dif	critical.dif	dif
IAMC-Monsoonal China		56.66302	84.47537	FALSE
IAMC-Northeast Asia		43.62044	65.13276	FALSE
IAMC-South Asia		218.59561	98.26057	TRUE
Monsoonal China-Northeast Asia		100.28347	80.20903	TRUE
Monsoonal China-South Asia		275.25864	108.84095	TRUE
Northeast Asia-South Asia		174.97517	94.61787	TRUE

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Supplementary Table 4. Statistical results of regional grain measurements by type, hulled and naked, and by time, All Time and After 1000 BC.

Hulled Length, All Time

Kruskal-Wallis	chi-squared	Df	p-value	n
	50.603	3	5.94E-11	400

Multiple comparison test after Kruskal-Wallis		P-value 0.05	
Comparisons	obs.dif	critical.dif	dif
IAMC-Monsoonal China	60.15983	99.20446	FALSE
IAMC-Northeast Asia	76.78303	35.72366	TRUE
IAMC-South Asia	18.86807	39.49907	FALSE
Monsoonal China-Northeast Asia	136.94286	100.21042	TRUE
Monsoonal China-South Asia	41.29176	101.61754	FALSE
Northeast Asia-South Asia	95.6511	41.96165	TRUE

Hulled Breadth, All time

Kruskal-Wallis	chi-squared	Df	p-value<	n
	45.913	3	5.92E-10	400

Multiple comparison test after Kruskal-Wallis		P-value0.05	
Comparisons	obs.dif	critical.dif	dif
IAMC-Monsoonal China	43.306069	99.20446	FALSE
IAMC-Northeast Asia	8.633613	35.72366	FALSE
IAMC-South Asia	89.200025	39.49907	TRUE
Monsoonal China-Northeast Asia	51.939683	100.21042	FALSE
Monsoonal China-South Asia	45.893956	101.61754	FALSE
Northeast Asia-South Asia	97.833639	41.96165	TRUE

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Supplementary Table 5 cotinued: Statistical results of regional grain measurements by type, hulled and naked, and by time, All Time and After 1000 BC.

Hulled Length, After 1000 BC				
Kruskal-Wallis	chi-squared	Df	p-value	n
	21.697	3	7.54E-05	240
			P-value 0.05	
Multiple comparison test after Kruskal-Wallis				
Comparisons		obs.dif	critical.dif	dif
IAMC-Monsoonal China		86.63214	71.61163	TRUE
IAMC-Northeast Asia		2.057	24.57406	FALSE
IAMC-South Asia		80.4125	67.29884	TRUE
Monsoonal China-Northeast Asia		88.68914	71.1416	TRUE
Monsoonal China-South Asia		167.04464	94.79649	TRUE
Northeast Asia-South Asia		78.3555	66.79847	TRUE

Hulled Breadth, After 1000 BC				
Kruskal-Wallis	chi-squared	Df	p-value<	n
	7.855	3	0.04911	240
			P-value 0.05	
Multiple comparison test after Kruskal-Wallis				
Comparisons		obs.dif	critical.dif	dif
IAMC-Monsoonal China		34.58786	71.61163	FALSE
IAMC-Northeast Asia		19.443	24.57406	TRUE
IAMC-South Asia		28.1175	67.29884	FALSE
Monsoonal China-Northeast Asia		54.03086	71.1416	FALSE
Monsoonal China-South Asia		62.70536	94.79649	FALSE
Northeast Asia-South Asia		8.6745	66.79847	FALSE

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Naked Length, All Time				
Kruskal-Wallis	chi-squared	Df	p-value<	n
	167.59	3	2.20E-16	1132
		P-value 0.05		
Multiple comparison test after Kruskal-Wallis				
Comparisons		obs.dif	critical.dif	dif
IAMC-Monsoonal China		200.1931	66.78585	TRUE
IAMC-Northeast Asia		140.1796	64.54138	TRUE
IAMC-South Asia		292.0912	104.92407	TRUE
Monsoonal China-Northeast Asia		60.0135	77.01011	FALSE
Monsoonal China-South Asia		492.2843	113.02224	TRUE
Northeast Asia-South Asia		432.2708	111.71064	TRUE

Naked Breadth, All Time				
Kruskal-Wallis	chi-squared	Df	p-value<	n
	69.039	3	6.86E-15	1132
		P-value 0.05		
Multiple comparison test after Kruskal-Wallis				
Comparisons		obs.dif	critical.dif	dif
IAMC-Monsoonal China		98.47067	66.78585	TRUE
IAMC-Northeast Asia		9.066864	64.54138	FALSE
IAMC-South Asia		256.364683	104.92407	TRUE
Monsoonal China-Northeast Asia		89.403805	77.01011	TRUE
Monsoonal China-South Asia		354.835353	113.02224	TRUE
Northeast Asia-South Asia		265.431548	111.71064	TRUE

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Naked Length, After 1000 BC

Kruskal-Wallis	chi-squared	Df	p-value<	n
	233.46	3	2.20E-16	843

Multiple comparison test after Kruskal-Wallis		P-value 0.05	
Comparisons	obs.dif	critical.dif	dif
IAMC-Monsoonal China	250.13854	58.42629	TRUE
IAMC-Northeast Asia	183.88722	54.10311	TRUE
IAMC-South Asia	138.68881	81.83259	TRUE
Monsoonal China-Northeast Asia	66.25133	59.9226	TRUE
Monsoonal China-South Asia	388.82736	85.79128	TRUE
Northeast Asia-South Asia	322.57603	82.90754	TRUE

Naked Breadth, After 1000 BC

Kruskal-Wallis	chi-squared	Df	p-value<	n
	71.784	3	1.77E-15	843

Multiple comparison test after Kruskal-Wallis		P-value0.05	
Comparisons	obs.dif	critical.dif	dif
IAMC-Monsoonal China	62.23536	58.42629	TRUE
IAMC-Northeast Asia	18.50531	54.10311	FALSE
IAMC-South Asia	211.34243	81.83259	TRUE
Monsoonal China-Northeast Asia	80.74067	59.9226	TRUE
Monsoonal China-South Asia	273.57779	85.79128	TRUE
Northeast Asia-South Asia	192.83712	82.90754	TRUE